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A low-carbon way to increase energy access: How to scale mini-grids in developing countries

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Abstract—Mini-grids are being promoted in developing countries to increase electricity access in remote areas (SDG 7), and to meet demand for productive use of energy in these areas (SDG 8). This paper shows that in addition, renewable energy-based mini-grids can substantially reduce carbon emissions by decreasing the dependence on fossil fuel-intense national grids (SDG 13). If they were to be deployed at their potential scale, the CO_2 equivalent savings potential is estimated to be up to 390 million metric tons per year until 2050 in sub-Saharan Africa and South Asia, *ceteris paribus*. Yet to date, few examples of financially sustainable mini-grids in developing countries exist. This paper argues that in order for mini-grids to reach their full potential, four main things need to happen: (1) business models need to focus on provision of physical electricity-based services in addition to merely selling electricity to improve the financial performance of mini-grids; (2) the regulations governing mini-grids in developing countries need to be enable rapid project development; (3) the market environment needs to be improved for both local and international companies; and (4) governments and international development agencies need to cooperate closely and include mini-grids as a core element of their electrification (and finance allocation) strategies.

Keywords—Mini-grids, renewable energy, energy business models

I. Introduction

Developing countries in sub-Saharan Africa and South Asia are projected to feature the fastest growing electricity demand in the world in the coming decades of up to 5% p.a. [1]. This demand increase stems from expanding access to electricity and using it for productive means to generate income. In South Asia, the electrification rate is roughly 85%, while it stands at 35% in sub-Saharan Africa [2]. Together, these two regions account for over 1 billion of the 1.2 billion people globally without access to electricity. The current share of fossil fuel-based electricity generation in sub-Saharan Africa is slightly above 70%, while it is roughly 80% in South Asia [2]. Hence, in both regions, there is a well-known potential conflict between the UN's goal of achieving universal access to modern energy (SDG 7) and its goal of combating climate change (SDG 13) [3].

All countries in sub-Saharan Africa and South Asia have submitted a Nationally Determined Contribution (NDC) on climate change to the United Nations in response to the 2016 Paris agreement. The vast majority of these NDC measures from developing countries relate to on-grid generation capacity, mostly by signalling an intend to increase renewable energy capacity instead of fossil fuels [4]. They are often conditional on receiving international funding. To allow developing countries to increase electrification rates and grow their current low per-capita electricity consumption, the associated CO_2 saving targets are usually defined in terms of a projected future generation mix rather than against a historic baseline.

This paper proposes a large-scale expansion of renewable energy (RE)-based mini-grids for developing countries as an additional climate change mitigation measure. Importantly, their unique synergies with increasing high-quality energy access imply that mini-grids need not be driven solely by climate change mitigation motivations, but also, and potentially predominantly, by the goal to increase energy access. Universal electrification is a high-priority goal on both the UN's developmental, as well as the affected national governments' political agendas [5, 6]. Available annual funds contributed towards this goal have almost quadrupled in the last 15 years in sub-Saharan Africa [7]. As over 80% of unelectrified people in South Asia and sub-Saharan Africa live in rural areas, electrification of remote areas needs to be the focal point of any efforts aimed at SDG 7. Mini-grids are known to be cheaper compared to grid extensions in many remote areas [8], and additionally are often more reliable and environmentally friendly alternatives. They furthermore are economically and environmentally superior to diesel generators which currently dominate the rural off-grid sector in developing countries.

After providing a brief background on RE-based mini-grids in section II, this paper estimates their CO_2 equivalent (CO_2e) saving potential in sub-Saharan Africa and South Asia of in section III. Building on novel qualitative interview as well as quantitative cost data from mini-grid developers as well as public sector stakeholders from sub-Saharan Africa, section IV summarises the main challenges and discusses the associated potential solutions of making mini-grids work at scale. A conclusion is offered in section V.

II. RE-based Mini-grid background

Access to electricity can be provided via one centralised grid or via off-grid technologies. The off-grid sector is divided into stand-alone systems such as Solar Home Systems (SHS) or diesel generators, and mini-grids. While each connected entity has its own power source in stand-alone systems, mini-grids connect several entities to one ore more shared power sources. Mini-grids exist in different sizes, ranging from below 5 kW with a few connections (often designed as a DC grid to serve demands such as lighting and phone charging) up to 10 MW with an AC distribution network spanning up to hundreds of kilometres. However, the upper capacity limit of mini-grids is subject to debate [9].

Total RE-based mini-grid installed capacity was estimated to be around 0.8 GW worldwide in 2017, providing access to around 9 million people globally [10]. A significant share of their capacity serves commercial and small-scale businesses. Currently, roughly 50% of all mini-grid capacity is based on hydro energy, roughly 40% is based on solar PV, and the remaining 10% run on bioenergy. Yet due to the abundance of solar energy in sub-Saharan Africa and South Asia, solar mini-grids are likely to be the dominating mini-grid technology by 2050. Solar mini-grids have grown from 11 MW installed capacity worldwide in 2008 to roughly 310 MW in 2017. There are 8,100 documented solar mini-grids, implying an average installed capacity of 38 kW [10]. Fig. 1 shows the schematic of a solar mini grid. As the generated power from solar PV cells (as well as from the associated batteries) is DC, most solar mini-grids include an inverter for more efficient AC electricity distribution as well as to be able to run AC appliances.

III. ROUGH-SIZING THE CO_2 SAVING POTENTIAL OF SOLAR MINI-GRIDS IN DEVELOPING COUNTRIES

This section provides an outline of how the CO_2e emission savings potential of mini-grids in developing countries was estimated. The point of this exercise is to provide a rough estimate rather than a detailed derivation. Due to their respective importance, the estimate is based on data from sub-Saharan Africa and South Asia. To rough-size the CO_2e saving potential, a four-step process was carried out, namely (A) gathering data on electricity demand projections in sub-Saharan Africa and South Asia, (B) deriving the range of total additional installed capacity requirements, (C) estimating the potential of mini-grids based on the total generation requirements, and (D) calculating lifetime CO_2e emission savings potential as a result of this mini-grid potential and the estimated on-grid generation mix. Fig. 2 shows the results of these four steps.

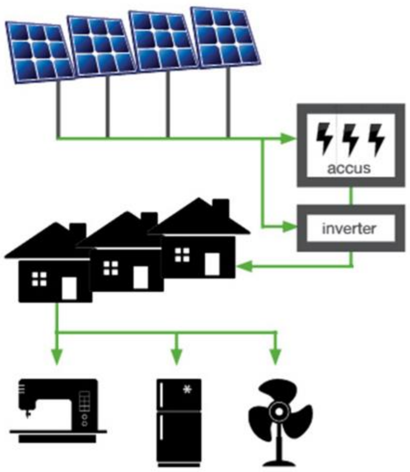


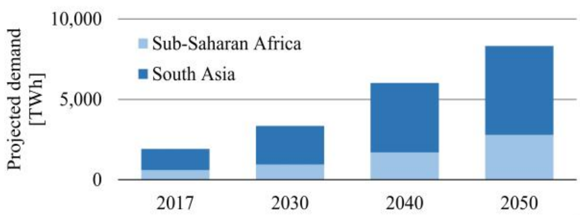
Fig.1. Solar mini-grid schematic (source: [11])

A. Future electricity demand

International energy associations such as the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA) and the World Energy Council (WEC) have been estimating worldwide electricity demand for the coming decades [1, 12, 13]. For the purpose of this paper, averages were used from these sources for each time period where multiple demand estimations were available for sub-Saharan Africa and South Asia. The energy agencies project a total demand of roughly 8500 TWh in 2050 for both regions, equating to a more than fourfold increase compared to 2019.

B. Additional installed capacity requirements

The electricity demand projection was translated into a range of new installed generation requirements until 2050. The current installed generation capacity mix and associated average capacity factors (see Table 1) were used to estimate an overall average capacity factor of both power systems, lowered by 10% in South Asia and 20% in sub-Saharan Africa due to aging plants and sub-optimal maintenance. This yielded an average capacity factor of 60% for the current sub-Saharan African, and 63% for the South Asian power system. As the generation mix is expected to shift more towards renewables in the coming decades, this average capacity factor is likely to slightly decrease. To estimate the additional installed capacity needs in 2030, 2040 and 2050 from the projected demand, an average capacity factor interval was used. It ranges from a 65% until 2050 in a high-carbon generation mix scenario to 55% in 2030, 52.5% in 2040, and 50% in 2050 in a low-carbon generation mix scenario. While the former is largely a *ceteris paribus* generation composition, the latter would imply that in 2050, solar energy (both solar PV and Concentrated Solar Power) and wind would dominate the generation mix in both regions (combined share of 50%), with renewables in total accounting for 75% of installed capacity (see [12]). Transmission and distribution losses are included in the estimates, as is a 20% reserve margin (which is low by international standards, but reasonable given that there is currently no reserve margin in sub-Saharan Africa). The currently installed capacity of 90 GW in sub-Saharan Africa and 395 GW in South Asia was subtracted to yield new capacity needs versus a 2017 baseline. For 2050, depending on the generation mix, an additional 1.2 TW (high-carbon) – 1.8 TW (low-carbon) of combined installed capacity is required (see Fig. 2).



	2017	2030	2040	2050
New capacity needs versus 2017 [GW]		210 - 280	770 – 1,000	1,200 – 1,800
Mini-grid potential [GW]		110	300	450
Potential av. annual CO_2e savings [mn. t]		**40 - 90**	**100 - 250**	**150 - 390**

Fig.2. Estimation of annual CO_2e savings potential from mini-grids in sub-Saharan Africa and South Asia against 2050 baseline (sources: [1, 7, 12, 13], author's calculation)

TABLE I. AVERAGE ASSUMED CAPACITY FACTORS

Generation technology	Assumed capacity factor
Coal	0.85
Natural gas	0.85
Oil	0.8
Nuclear energy	0.9
Solar PV	0.25
Solar Concentrated Power	0.5
Biomass	0.5
Wind	0.3
Hydro	0.6

C. *Potential of RE-based mini-grids*

Mini-grids are being used for small-scale industrial, commercial and residential uses. In 2010, IEA has quantified the potential of mini-grids to account for 40% of all new generation in sub-Saharan Africa, and 44% in South Asia between 2011 and 2030 [14]. Despite the technological feasibility of such shares, they seem unlikely to be attainable. For the purpose of this exercise, a more conservative fraction of mini-grid generation was used. It was set to half of IEA's shares as this translates to almost exactly matching the current per-annum percentage growth of solar mini-grids until 2030, and a subsequent decline in percentage growth. In addition, as mini-grids are known to be significantly cheaper than off-grid diesel generation in most instances, half of the current roughly 60 TWh of global off-grid diesel generation is estimated to be replaceable by RE – based mini-grids. As a result, the mini-grid generation potential is estimated to be roughly 1,350 TWh of the total 6,400 TWh new electricity demand in 2050 in sub-Saharan Africa and South Asia. This translates to an installed capacity potential of 450 GW for RE-based mini-grids in 2050 given an average 35% capacity factor.

D. *Average annual CO_2e savings potential*

The CO_2e emissions savings potential originates from reducing the need for fossil fuel-heavy on-grid capacity and off-grid diesel generation. The savings were calculated based on the low-carbon and the high-carbon generation mix scenarios used to calculate the total installed capacity requirements (section III.B). Average CO_2e emissions savings were taken from [15]. Including 10% transmission and distribution losses for on-grid technologies, 1 TWh consumed incurs 0.73 million metric tons more CO_2e compared to solar mini-grids in the high-carbon generation mix scenario, and 0.38 million metric tons of CO_2e more in the low-carbon generation mix scenario. Given the estimated mini-grid potential, this implies annual average savings of 150 – 390 million tons of CO_2e every year between 2019 and 2050 versus a 2050 baseline. This result agrees with an extrapolation of empirical findings published by the Energy and Environment Partnership (EEP) Africa group [16]. The report reviewed the 19 early-stage mini-grids within EEPs portfolio in Africa.

IV. THE MAIN CHALLENGES FOR SCALING, AND THEIR SUGGESTED SOLUTION

Challenges of existing mini-grids are well documented [9, 16]. They include (A) the difficulty of recovering investments from mini-grids, (B) regulatory issues, (C) a nonconducive market environment, and (D) the strategic focus of both international development organisations and national governments on on-grid over off-grid electrification. After briefly illustrating each challenge, this section presents a solution outline addressing these challenges. They are in part based on novel primary qualitative and quantitative data obtained from semi-structured interviews and written communications with several mini-grid developers and public sector actors active in sub-Saharan Africa in January and February of 2019.

A. *Difficulty of recovering investments from mini-grids*

1) *The challenge*

RE-based mini-grids in general, and solar mini-grids specifically, are currently usually not able to recover their costs [9, 16]. In small-scale cases, even the annual expenses (interest on capital and OPEX) cannot be recovered from the revenue collected from selling electricity. Table II quantifies this dilemma in its second column using an exemplary 30 kW solar mini-grid. The data is largely based on actual investment figures obtained from a mini-grid developer active in several developing countries. It is noteworthy that project development, electrical system components (batteries, inverters, controllers and meters), distribution network and logistics make up roughly 85% of the total investment costs, while solar PV modules account for less than 10% (see also [16]).

2) *Solution outline: Innovative business models*

There are two options for businesses to increase revenues, namely increasing sales volume and increasing the value per unit sold. Firstly, it is important for mini-grid developers to waste as little electricity as possible. Rather than relying solely on residential customers, mini-grids which have relied on a combination of customers have fared better due to higher and more constant demand. An increasingly popular model combines a large-scale anchor customer such as a telecommunications tower, several small businesses, as well as residential consumers (sometimes referred to the "ABC" distribution model – Anchor, Businesses, Consumers). Yet even a system operating at full capacity throughout its lifetime is currently unlikely to recover all of its costs. Hence, secondly, until the costs of mini-grids decreases substantially, the focus should be on increasing the value of their generation. There is little potential to increase the tariff charged to customers due to the socio-political goal to maintain national tariff equality. Instead, developers can alter their value proposition: Rather than selling only electricity, they should also sell services which require electricity as an input. Crucially, they need to provide the CAPEX necessary to do so in order to sell these services due to the low capital availability of their potential customers.

The third column of Table II illustrates this altered value proposition. These figures are again based on the mini-grid developer who faced the situation apparent in the second column of Table II. In addition to constructing the mini-grid, the developer has built a cooling facility next to the solar PV cells, using about 20% of the system's generated electricity. The facility houses 130 cooling boxes which can be rented out by customers at a certain cost, enabling them to increase the shelf-life of their agricultural produce (mainly fruits)

TABLE II. FINANCIAL PERFORMANCE OF A 30 KW SOLAR MINI-GRID

	Conventional value proposition: Selling kWhs	*Innovative value proposition: Selling kWhs and services*
System size	30 kW solar and battery storage	30 kW solar and battery storage plus cooling facility
CAPEX	260,000 USD	280,000 USD (plant plus cooling facility)
Capital structure	130,000 USD equity, 130,000 USD debt at 10% for 5 years	130,000 USD equity, 150,000 USD debt at 10% for 5 years
Av. interest during first 5 years p.a.	7,800 USD	9,000 USD
OPEX p.a.	12,000 USD	14,000 USD
Generation for direct sales p.a.	71 MWh	56 MWh
Tariff charged	0.28 USD/kWh	0.28 USD/kWh
Revenue from direct sales p.a.	18,300 USD	15,700 USD
Generation for services p.a.	-	15 MWh
Revenue from services p.a.	-	14,500 USD
Total revenue p.a.	18,300 USD	30,200 USD
Payback period	*Only 60% of CAPEX recovered after 25-year project lifetime*	20 years[a]

[a] This number is entirely based on the example calculation in Table II and can significantly decrease as solar mini-grids become technologically more mature, regulatory and market conditions improve and off-grid electrification receives similar financial support per connection as grid-expansion

from 3 days to two weeks. As Table II shows, the mini-grid developer increases annual revenue by 65% while increasing CAPEX by only 8%. The resulting payback period of 20 years does not constitute a lucrative investment project as is, yet the example shows the significant potential of this business model. It is crucial to note that this payback period for developers will decrease significantly as mini-grids move from technological novelty to maturity. Further decreases can be achieved by implementing the solution outlines discussed in the following three sub-sections.

Following this example, there is a need to expand this business model idea towards any type of additional service which may be suitable to offer as a service. Different productive use activities which require upfront CAPEX for appliances may focus on agriculture (such as blending, milling, cooling, drying, irrigation, oil seed processing and water pumping), manufacturing (carpentry, electrician and mechanics services, sewing and welding) and services (communication, cooking, entertainment, hair dressing, internet provision and vending). Depending on the area where a mini-grid is to be deployed, those economic activities with potential for productive use of energy need to be identified and ranked by comparing required CAPEX, electricity demand and projected revenue from the respective service.

B. *Regulatory issues*

1) *The challenge*

The idea of large-scale mini-grid roll-outs is relatively novel in most developing countries. The regulatory frameworks governing mini-grid development and operations are currently being crafted or frequently re-visited in most countries due to high market dynamics and the low level of experience with mini-grids. For instance, even a country with comparably well-established regulatory capacities such as Uganda currently does not have regulations in place to allow a straight-forward implementation of the novel business model described in section IV.A. The requirements to obtain an official mini-grid license differ significantly in different countries. For example, one developer active in an East African and a West African country reported that they needed over 12 months to put together a 500-page document to obtain a small-scale mini-grid license in the East African country, while it took one week and a 9-page document in the West African country to do the same. Long licensing processes directly increase project development costs. Several key issues such as site selection and managing the integration of mini-grids into the national grid, should the grid arrive at the location of the mini-grid before the end of the mini-grid's lifetime, are not clearly regulated in most countries.

2) *Solution outline: Efficient licensing*

The licensing and permitting process has to be standardised and made more transparent and efficient. A balance needs to be struck between enabling rapid mini-grid deployment and safeguarding against the main risks. Crucially, consistent rules need to be implemented on site selection, chargeable tariffs and potential feed-in tariffs in the future. In South Asia, a cross-country taskforce entitled "Regulatory Cooperation to Facilitate Knowledge sharing, addressing Cross cutting Energy/Electricity Regulatory Issues and Capacity Building in South Asia" has recently been formed. In sub-Saharan Africa, such international cooperation is rare, but should be fostered to develop binding guidelines on successful regulations across sub-Saharan Africa.

C. *Nonconducive market environment*

1) *The challenge*

The market environment is often not conducive for cost-efficient deployments of mini-grids. In most developing countries, import duties on solar mini-grid components are high. Even where solar PV panels are exempt from import taxes, batteries, inverters, controllers and other equipment responsible for the majority of module cost often are not. At the same time, there is limited domestic support for infant industries in these areas to provide local alternatives. Furthermore, local banks are either not willing or not able to provide mini-grid developers with affordable local currency loans.

2) *Solution outline: Enhancing local trade*

Import duties have often been used to protect domestic infant industries. However, in a situation where almost no in-country solar PV, battery, inverter or controller manufacturers exist, these duties jeopardise both international developers as well as local retailers in the mini-grid industry. The duties are passed on to the consumer and increase the cost of a service to satisfy basic human needs. It seems more sensible to drop import duties on components and provide public subsidies to local infant manufacturing businesses in order to help them become competitive with international players. An important step to lower mini-grid cost would be to enable regional free trade where the different components for mini-grids can be sourced from different developing countries. Such a free-trade zone has existed in South Asia since 2004, and is about to come into effect in Africa. However, electrical equipment constitutes one of the largest items which are not or only partly covered by this free-trade agreement the South Asia.

In terms of finance availability, as soon as mini-grids move beyond pilot-stage, obtaining local currency finance at reasonable terms would greatly lower the capital costs and associated risks. Efforts like the Rwandan government's commitment to establish low-interest loans for mini-grid developers are crucial.

D. Strategic focus on on-grid electrification

1) The challenge

When compared to on-grid capacity, mini-grids are significantly underrepresented in national energy system expansion plans in developing countries [17]. Decade-long experience with on-grid electrification, as well as its comparably straight-forward, centralised governance have led to off-grid electrification mainly being left to the private sector. Peters et al. make the important point that on-grid expansion has never been intended or designed to be able to recover cost over a short timeframe [9]. Rather, grid-extension serves as the premier means to deliver the public good of electricity access, with the overwhelming majority of finance originating from public sources [7]. Consequentially, while perceptions around the usefulness of off-grid electrification have started to change, financial commitments from the national or international public sector remain a miniscule fraction of total power sector spent [7].

2) Solution outline: Use on-grid subsidies for off-grid

Contrary to preferences of many national governments in developing countries, various planning studies have found that mini-grids already constitute a cheaper electrification alternative than extending the national grid for many remote areas [8, 14]. This finding is especially true where studies have integrated on-grid and off-grid planning in their model [18]. The trend of mini-grids being financially superior compared to on-grid electrification in many remote areas in developing countries is certain to continue given the expected cost decrease of mini-grids in the future.

The disparity between current national electricity tariffs and the higher tariffs mini-grid developers would need to charge to recover their costs is, at least in part, driven by the high level of public subsidies for on-grid electrification. These on-grid subsidies exist in the form of public taxpayer money (a financial equivalent of a grant) and concessional loan finance from donor agencies. While data on the total level of subsidies in the on-grid sector in developing countries is not available, providing a similar per-kWh subsidy in the off-grid sector would significantly lower the mini-grid developer's required break-even tariff. Governments and international donor agencies are required to work closely together to ensure an inclusive allocation and efficient usage of such subsidies. An early example of such a subsidy shift, albeit limited in size, is the Ugandan Rural Electrification Agency's commitment to build the mini-grid's distribution network (yet not including wiring and metering in households). In addition to reducing CO_2e emissions, added benefits of this subsidy shift would include increasing energy access in remote areas (SDG 7), directly fostering productivity growth in low-income areas in developing countries (SDG 8) and a lower risk of corruption apparent in large-scale energy projects. Mini-grids are thus able to create much more win-win scenarios for the public sector and local as well as international private companies than are currently being realised.

V. CONCLUSION

Rapidly rising demand in developing countries in South Asia and sub-Saharan Africa warrant climate friendly solutions without compromising economic development. This paper has argued that renewable energy-based mini-grids constitute a promising, yet currently underutilised alternative to grid-based electrification with significant carbon emission savings potential. Mini-grids are able to meet domestic, commercial and small-scale industrial demand and are often cheaper in providing access to remote areas than grid extension. The average CO_2 equivalent emission savings potential of large-scale mini-grid deployment was estimated to be between 150 – 390 million metric tons per year between 2019 and 2050 against a 2050 baseline.

To realise this potential, this paper has presented four solution outlines to current challenges of mini-grids. Neither the challenges nor the solutions are technical in nature, but rather focus on the design of innovative business models, regulations and energy policies. Firstly, mini-grid developers increase the chances of making their products bankable by being ready to further increase their CAPEX commitment up front to offer tailored electricity-based services to its customers. This approach secures more value per kWh of electricity generated than the prescribed tariff allows them to. Secondly, the regulations governing mini-grids need to focus on efficient project delivery, ideally equipped with higher level standardisation and transparency. Thirdly, the market environment for both local and international businesses needs to be improved with targeted import tax reductions for regional trade and subsidy schemes depending on the situation in each country. Fourthly, the subsidies both national governments in developing countries as well as international development agencies are committing towards the on-grid sector should be equally applied to the mini-grid sector, rather than leaving mini-grids entirely to the private sector. This would not only lead to lower CO_2 emissions compared to on-grid electrification, but also increase reliable energy access more efficiently.

If implemented in conjunction, these measures would significantly enhance the opportunity to make mini-grids bankable and deploy them at scale.

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